I. CONSIDERATIONS OF IMPLEMENTING AN ADDITIONAL READOUT WIRE PLANE IN THE SINGLE-PHASE LARTPC

In this section, we summarize the considerations of implementing an additional induction wire plane in the single-phase LArTPC to enhance its performance.

In the current design of the DUNE single-phase LArTPC, there are three readout wire planes. In front of these readout planes, there is a grid wire plane added in order to shape the impulse field response function. On the back of these readout planes, there is a wire plane to prevent the collection of ionization charge generated inside the anode plane assembly (APA). The bias voltage are applied on these (five) wire planes, so that the ionization electrons will drift at 100% transparency through the grid plane and first two readout wire planes before all collecting on the last readout plane. The first two readout wire planes are commonly referred to as the induction plane and the last readout wire plane is referred to as the collection plane. The impulse field response function is with bipolar and unipolar shape for the induction and collection plane, respectively.

There are three reasons that adding one more induction wire plane will significantly increase the performance of the single-phase LArTPC. They are:

- Ambiguities reduction,
- More resistance to dead channels,
- Increase the acceptance for the induction signal through robust ROI finding.

In the following, we will briefly describe each reason.

In single-phase LArTPC, the 1D wire-based readout is necessary due to the financial constraint on the total number of channels that can be afforded and the physical constraint on the total electronics consumption power that can be allowed in the LAr. Compared to the 2D pad-based readout, the (multiple) 1D wire-based readout significantly reduce the total number of channels at the cost of increase in ambiguities. Figure 1 shows the number of reconstructed potential hits as a function of the number of real hits in a fixed time slice. A reconstructed potential hit is defined as a hit where multiple hit wires (one from each readout plane) cross. These wires may not be necessarily originated from the same real hit. Therefore the number of reconstructed potential hits is larger than the number of real hits. Different solid curves represent different number of total readout wire planes from 2 to 6. It is clear that more wire planes would reduce the ambiguities. For DUNE (3 wire plane case), the number of potential hits roughly ranges from one to fifty for ν_e charged-current interaction. Therefore, increasing the number of readout wire planes from three to four represents a significant step towards reducing the ambiguities, which is crucial for clearly identifying activities near the neutrino interaction vertex (one of the busiest region).

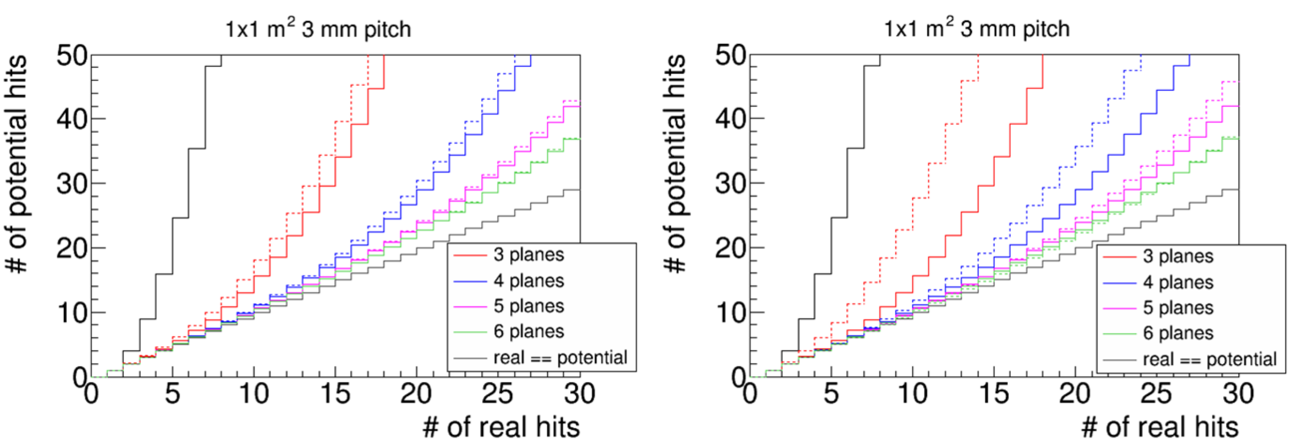

FIG. 1. Illustration of ambiguities with number of reconstructed potential hits as a function of the number of real hits in a 1D wire-based readout detector. Different curves represent different number of wire planes from 2 (black) to 6. The no-ambiguity situation where the number of reconstructed potential hits is exactly the same as the number of real hits is labeled as "real == potential". The solid curves represent the situation when all the channels are functioning. The dashed curves represent the situation where some of the channels are dead. The left (right) panel represent the situation where 1% (5%) of the channels are dead. See text for more discussions.

In practice, it is unrealistic to have 100% working channels for a 10kt detector. For example, in the current-generation large LArTPC experiments, the ratio between the number of dead channel and the number of total channels is above 10%. In the next-generation large LArTPCs, we expect this ratio to be significantly reduced. Nevertheless, it is unrealistic to assume zero dead channels. Assuming "p" is the efficiency of a single wire plane, the volume efficiency can thus be estimated as $\epsilon_n = p^n$ given "n" number of wire planes. This volume efficiency can be enhanced if less number of planes is required in the reconstruction. For example, if we require one less readout plane to be used in the reconstruction, the volume efficiency is $\epsilon_{n-1} = p^n + n \cdot (1-p) \cdot p^{n-1}$, which can be much higher than ϵ_n. However, the increase in the volume efficiency is at the cost of increasing number of ambiguities. Assuming F_n represents the number of reconstructed potential hits given "n" number of wire planes, the number of reconstructed potential hits using one less plane in the reconstruction can be estimated as $(F_n + (1-p) \cdot n \cdot (F_{n-1} - F_n)) \cdot \epsilon_{n-1}$. Basically, when one less readout wire plane is required in the reconstruction, the number of reconstructed potential hits F_n will receive an leakage from that of the "n-1" wire plane F_{n-1}. The left (right) panel of Fig. 1 illustrates the situation for 1% (5%) dead channels. Since the ambiguity with three wire planes is much reduced compared to that of the two wire planes, the four wire planes are much more robust against the potential dead channels compared to the three wire planes case.

Beside the existence of ambiguity due to the 1D wire-based readout, another big challenge of the single-phase LArTPC is the processing of the induction wire plane signal. When the impulse field response of the collection wire plane is unipolar, the impulse field response of the induction wire plane is bipolar. The integration of the induction impulse response function over time is close to zero, as none of the ionization electron is collected by the induction plane. Depending on the original ionization electron distribution, the positive lobe of field response could cancel with the negative lobe leading to overall smaller signal heights compared to those from collection wire plane. Therefore, the induction wire plane signal is much more sensitive to noise compared to the collection wire plane signal. The implementation of the cold electronics that significantly reduces the electronic noise as shown in Ref. [1] represents a major step towards improving the induction wire plane signal. Furthermore, the implementation of the 2D deconvolution in the signal processing chain [2] represents another significant step in improving the induction wire plane signal. Despite these efforts, there is still an limitation in the induction plane signal, as the signal to noise ratio becomes smaller with the increase of the signal (time) length. In order to maximize the signal to noise ratio in the induction plane, the region-of-interest (ROI) technique is crucial. A ROI is a region just contains the signal, so that the electronic noise, especially the low-frequency one, is minimized during the signal processing. In practice, while finding ROI is a relative simple task for a short signal, it is much more difficult to reliably finding ROI for a long signal due to the smaller signal to noise ratio. Adding a new readout wire plane can significantly improve the ROI finding. Recall that a real ionization signal would generate currents on each wire plane simultaneously [1]. Therefore, a long ROI can be built from short ROIs from the other wire planes requiring the wires from different planes crossing at the same point. This technique works for tracks that are not traveling completely perpendicular to a wire plane. In principle, this technique can work for the three readout wire planes situation. In this case, the ROI has to be built from the other two wire planes. However, as shown in Fig. 1, the number of ambiguities for three wire plane is much reduced than that of the two wire planes. Therefore, the aforementioned robust ROI finding technique is much less powerful in the three readout wire planes case. Add one more induction wire plane can significantly improve the situation.

Technically, in the current single-phase APA design, the grid plane, which is at the correct bias voltage, can be converted into the fourth induction wire plane once it is read out. Ref. [2] shows that the signal processing of the first induction wire plane in MicroBooNE (without a grid plane) is successful. Therefore, the original requirement of shaping the induction impulse field response with a grid plane can be relaxed. The angle of the grid plane wire will need to be changed so that there is no degeneracy in the wire orientation among all readout planes.

Based on these studies, we also emphasize it is important to consider three or more readout planes for the dual-phase LArTPC design. Although the dual-phase design is free of the complication from induction wire planes, the considerations of reducing ambiguities due to 1D wire-based readout still apply.

[1] "Noise Characterization and Filtering in the MicroBooNE TPC", MicroBooNE NOTE 1016-PUB `http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1016-PUB.pdf`.

[2] "A Method to Extract the Charge Distribution Arriving at the TPC Wire Planes in MicroBooNE", MicroBooNE NOTE 1017-PUB, `http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1017-PUB.pdf`.

[1] The coincidence is after taking into account the short time needed for ionization electrons traveling from one wire plane to the next.